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# KBO binaries: are they really primordial ?

J-M. Petit<sup>1</sup>, O. Mousis<sup>1</sup>

<sup>1</sup>Observatoire de Besançon, France

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## Abstract

Given the large orbital separation and high satellite-to-primary mass ratio of all known Kuiper Belt Object (KBO) binaries, it is important to reassess their stability as bound pairs with respect to several disruptive mechanisms. Besides the classical shattering and dispersing of the secondary due to a high-velocity impact, we considered the possibility that the secondary is kicked off its orbit by a direct collision of a small impactor, or that it is gravitationally perturbed due to the close approach of a somewhat larger TNO.

Depending on the values for the size/mass/separation of the binaries that we used, 2 or 3 of the 8 pairs can be dispersed in a timescale shorter than the age of the solar system in the current rarefied environment. A contemporary formation scenario could explain why we still observe these binaries, but no convincing mechanism has been proposed to date. The primordial formation scenarios, which seem to be the only viable ones, must be revised to increase the formation efficiency in order to account for this high dispersal rate. Objects like the large-separation KBO binary n2001 QW<sub>322</sub> must have been initially an order of magnitude more numerous.

If the KBO binaries are indeed primordial, then we show that the mass depletion of the Kuiper belt cannot result from collisional grinding, but must rather be due to dynamical ejection.

# I Introduction

Over the past decade, the Edgeworth-Kuiper belt has changed status, from a theoretically predicted entity to a collection of more than 700 comets orbiting beyond Neptune. At first, those (not so) small icy bodies were thought to be lonely wanderers, except for the pair Pluto-Charon. At the end of 2000, Veillet *et al.* (2002) found the first Kuiper Belt Object (KBO) satellite. This discovery was followed by seven others in the following 24 months, representing about 1% of the total known KBO population. The main characteristics of the KBO binaries, when compared with the asteroid binaries, are large separations ( $\sim 5,000$  to  $130,000$  km, or  $\sim 20$  to almost  $2,000$  times the primary radius - of order a few to 10 for asteroids) and high satellite-to-primary mass ratio of 0.1 to 1 ( $\sim 10^{-4}$  to  $10^{-3}$  for asteroids).

The set of known KBO binaries suffers from a very strong observational bias. KBO binaries with a small separation are impossible, or at least very difficult to detect as binaries because of their large distance to Earth. Their angular separation is smaller than the typical seeing, and still smaller than the diffraction limit (achievable with Adaptive Optics) if the separation is comparable to that of the asteroid binaries. Likewise, KBO binaries with low satellite-to-primary mass ratios cannot be recognized as binaries, because the secondary falls beyond the limiting magnitude of most observations. However, the very existence of the known binaries is a great novelty with respect to what is known in the asteroid belt or in the NEO population. This has prompted several authors to study their formation mechanisms (Goldreich *et al.*, 2002; Stern, 2002; Weidenschilling, 2002). Goldreich *et al.* and Weidenschilling concluded that collisions in the current Edgeworth-Kuiper cannot account for the large number of binaries found, nor for their large separation and high satellite-to-primary mass ratios. They proposed various mechanisms that must have occurred in the late stage of the formation of the solar system, at the end of the accretion phase. According to Goldreich *et al.* and Weidenschilling, the binaries would be primordial. Although contemplating similar primordial scenarios, Stern favors more contemporary collisional formation mechanisms, and reconcile the number of required impactors with the actual number of bodies by assuming a surface albedo of the binaries to be  $\sim 15\%$ , 2 to 4 times larger than usually assumed.

Once formed, a binary object can disappear either because one of the components (usually the secondary) is destroyed (shattered and dispersed) through a high velocity impact, or the pair gains enough orbital energy to become unbound, due to the close approach or direct collision of another object. For asteroids, the major mechanism to eliminate a binary is the destruction of the secondary through high-velocity impacts. Since it seems well established that all known KBO binaries cannot be efficiently collisionally destroyed in less than 4 Gyr, all work to date have assumed that the KBO binaries would be stable over the age of the solar system, except for Weidenschilling (2002), who

mentioned, without any development, the possibility of disrupting the most loosely bound binaries. We show that long term stability is not guaranteed, and some of the KBO binaries may very well have lifetimes of order 1-2 Gyr.

In the present work, we estimate the stability of these binaries with respect to several dispersal mechanisms. The data describing the known binaries and their dynamical and collisional environments are listed in Sect. II. Besides the classical shattering and dispersing of the secondary through a direct collision, we also consider the possibility that the secondary is knocked off its orbit by a direct collision of a rather small impactor, or is gravitationally perturbed by the close approach of a somewhat larger TNO. All these mechanisms are described in Sect. III. In Sect. IV, we present the lifetimes of the KBO binaries with respect to all three disruption mechanisms, both in the current rarefied and in the denser initial environments. We discuss the implications of these results on the formation scenarios in Sect. V. Finally, a summary of our findings is given in Sect. VI.

## II The facts

To address our goal, we first need to know the parameters defining the binaries, and then the population of potential impactors. The binary parameters we use here (Table 1) are from two different compilations for the first seven of them, the first one by Merline *et al.* (2003), the second one by Stern (2002), yielding different sizes, masses, and separations.

The last binary 2001 QC<sub>298</sub>, not included in these compilations, was discovered in October, 2002, and reported by Noll *et al.* (2003). Very little information is given in the discovery announcement. From the published magnitude and distance, we estimated the equivalent radius of the pair  $R_{eq} = \sqrt{R_P^2 + R_S^2}$  to be 212 km, assuming an albedo of 0.04, the usual default value for KBOs. The separation projected on the sky is estimated to be  $5000 \text{ km} \pm 2000 \text{ km}$ . The difference in magnitude is not known to us. Hence we chose two different cases, at the limits of the interval for known binaries: zero magnitude difference at one end of the range, and 2.2 magnitude difference at the other extreme, the largest known magnitude difference for KBO binaries. The resulting parameters are displayed in last line of Table 1.

The number of objects in the Edgeworth-Kuiper belt is not yet very well known. For the sake of simplicity and to allow comparison with previous work, we use the same differential size distribution as proposed by Weissman and Levison (1997), and Durda and Stern (2000), *i.e.* a two-component power law of the form:

$$N(r_i) \propto r_i^b dr_i \quad (1)$$

where  $b = -3$  for  $r < r_0$  and  $b = -4.5$  for  $r > r_0$ , with  $r_0 = 5 \text{ km}$ . The differential size distribution is assumed to be continuous at  $r = r_0$ . Following Durda and Stern (2000), the

normalization constant should be at least 70,000 objects with radius larger than 50 km, and perhaps twice that many. So we use  $10^5$  objects larger than 50 km in radius.

The final piece we need to estimate the number of collisions on a given target from a given set of impactors is the intrinsic collision probability. This number depends on the actual orbital distribution of the TNOs, and is therefore not well determined. It also depends on the location of the target in the belt. Here, we use the average value proposed by Farinella *et al.* (2000)

$$\langle P_i \rangle = 1.3 \times 10^{-21} \text{ km}^{-2} \text{ yr}^{-1}. \quad (2)$$

### III Disruption mechanisms

In this work, we consider three different ways (Fig. 1) of eliminating a KBO binary.

- The first one is the shattering of the secondary by a collision, followed by the dispersing of the resultant fragments. This possibility has been studied at length in previous works, in particular in the framework of the asteroid belt. Davis and Farinella (1997) show that bodies of radius larger than 50 km cannot be shattered and dispersed in the current dynamical and collisional environment. Since all binaries considered here have a secondary larger than 50 km in radius, it is clear that this process cannot be an efficient mechanism for eliminating the known KBO binaries. However, we consider this case as a reference, and as a mean of comparison with the other mechanisms. We use the value of  $Q_D^*$  for ice (minimal energy per unit mass of target to shatter and disperse the target) given by Benz and Asphaug (1999) to compute the required minimum impactor size:

$$Q_D^* = Q_0 \left( \frac{R_{pb}}{1\text{cm}} \right)^\alpha + B\rho \left( \frac{R_{pb}}{1\text{cm}} \right)^\beta. \quad (3)$$

$R_{pb}$  is the radius of the *parent body* to shatter and disperse, expressed in cm and  $\rho$  is the density of the parent body (in g/cm<sup>3</sup>).  $\alpha$ ,  $\beta$ ,  $B$  and  $Q_0$  are constants determined by a fit of results of numerical experiments, for impact velocity of 500 m/s and 3000 m/s. Since we will use impact velocities of 500 m/s and 1500 m/s (see below), the values of the parameters for the latter case are derived by linear interpolation from those given by Benz and Asphaug.

- The second mechanism is the collision of a small projectile, not big enough to shatter the secondary, but that gives enough momentum to unbind the secondary from the primary (Fig. 1b). For all known KBO binaries, it is easier to unbind the secondary than to send it colliding with the primary, i.e.  $e \rightarrow 1$ . When an impactor of mass  $M_i$  hits the secondary of mass  $M_S \gg M_i$ , the secondary undergoes a change in velocity

of  $\Delta \mathbf{V} = M_i \mathbf{V}_i / M_S$  where  $\mathbf{V}_i$  is the impactor's relative velocity. At this point, it is convenient to introduce the total mass of the binary,  $M = M_P + M_S$ , where  $M_P$  is the mass of the primary, and the reduced mass  $\mu = M_P M_S / (M_P + M_S)$ . Before the kick, we assume the secondary to be on a circular orbit around the primary, with speed  $V_S = \sqrt{GM/r}$ , where  $G$  is the gravitational constant, and  $r$  the separation between the primary and the secondary. The velocity after the kick is  $\mathbf{V}'_S = \mathbf{V}_S + \Delta \mathbf{V}$ . We look for a value of that velocity such that the total energy of the system vanishes, that is:

$$\frac{1}{2} \mu (V'_S)^2 = \frac{GM_P M_S}{r} = \mu (V_S)^2 \quad (4)$$

(circular initial orbit). The square modulus of the velocity is given by

$$(V'_S)^2 = (V_S)^2 + (\Delta V)^2 + \mathbf{V}_S \cdot \Delta \mathbf{V} = (V_S)^2 + (\Delta V)^2 + V_S \Delta V \cos \theta, \quad (5)$$

where  $\theta$  is the angle between the impactor's and the secondary's velocities. Averaging over all impact directions, we obtain

$$\langle \Delta V \rangle = V_S \frac{\sqrt{5} - 1}{2} \simeq 0.62 \sqrt{\frac{GM}{r}}. \quad (6)$$

So finally, the average impactor's mass necessary to dislodge the secondary from its orbit by direct collision is

$$M_i = 0.62 \frac{M_S}{V_i} \sqrt{\frac{GM}{r}}. \quad (7)$$

- The last possibility is gravitational perturbation from an encounter with a third body, that will transfer enough energy to the binary to unbind it (Fig. 1c). We have performed numerical integrations of the 3-body problem to determine the unbinding gravitational cross section for a perturber of mass  $M_i = 10^{19}, 10^{20}, 10^{21}$  and  $10^{22}$  kg, with velocity  $V_i$ . For each value of the mass and incoming velocity, we have selected a set of impact parameters, from 150 to 660,000 km, with 1.5 ratio increments. For each impact parameter, we ran 10,000 simulations with all other parameters taken at random, to evenly sample the space of possible orientation. Integrations were performed using the well-known general purpose, self-adaptive Bulirsch–Stoer integrator (Stoer and Bulirsch, 1980) with relative precision of  $10^{-12}$ . From this we determined the probability of disruption of the binary as a function of the impact parameter. Fig. 2 shows this probability for 4 different masses of the projectile ( $10^{19}, 10^{20}, 10^{21}$  and  $10^{22}$  kg) arriving at 500 m/s on 2001 QW<sub>322</sub>. This case has been chosen as being representative of all cases, with no particular behavior. The probability of disruption  $P(h)$  for impact parameter  $h$  determines the gravitational disruption cross-section

$$\sigma = \int_0^\infty 2\pi h P(h) dh, \quad (8)$$

from which one can derive the frequency of occurrence of such disruptions, and finally define the equivalent radius  $R_g = \sqrt{\sigma/\pi}$ . Note that on Fig. 2, the distance between curve decreases between the last two on the right. This results in a maximum efficiency (minimum lifetime) for the gravitational disruption mechanism somewhere in the range of mass studied.

## IV Lifetimes

In order to determine the frequency of disruption events, or conversely the expected lifetime with respect to disruption, one need to know the number of projectiles, the disruption cross-section, and the intrinsic encounter probability. Given the size of the projectile, one can easily determine the number of such projectiles using the size distribution given by eq. (1). For the first two disruption mechanisms (direct collision), the disruption cross-section is simply the collisional cross-section, that is the physical cross-section  $\pi(R_S + R_i)^2$  times the gravitational focussing  $(1 + V_{esc}^2/V_i^2)$ , where  $V_{esc}$  is the escape velocity of the pair (secondary, impactor). However, the  $\pi$  factor is already included in the definition of  $\langle P_i \rangle$ . Hence we only need to compute  $(R_S + R_i)^2$  times the gravitational focussing. For the third disruption mechanism, we compute  $\sigma/\pi$  from eq. (8).

For each set of binary parameters (Merline *et al.*, 2003 and Stern, 2002), we have estimated the impactor size and/or the disruption cross-section for the three mechanisms, assuming encounter velocities of 500 m/s and 1500 m/s which roughly bracket the actual encounter velocities in the present day Edgeworth-Kuiper Belt. In Table 2 we report the shortest lifetime and the corresponding impactor size for each mechanism for the seven KBO binaries listed by Merline *et al.* (2003) and Stern (2002).

The case of 2001 QC<sub>298</sub> is presented in Table 3. Here we have considered four different sets of binary parameters: the two sets of radii from the last line of Table 1, and a density of either 1 g/cm<sup>3</sup> or 2 g/cm<sup>3</sup>. For each of these sets, we have run simulations for the same encounter speeds as before, and we report the shortest lifetime for each parameter set.

The first obvious trend is that ejection of the secondary due to a direct collision is the most efficient way to disrupt a KBO binary. As was already well known, we find that collisional shattering and dispersing of the secondary is not efficient here. Gravitational disruption is also inoperative here because of the large size needed for the projectile, and the steep slope of the size distribution at large sizes. Interestingly, thanks to the high encounter speed, we never saw an exchange between the projectile and one of the components of the binaries in any of our integrations.

As can be seen from the tables, 2 or 3 of the 8 known KBO binaries have mean disruption lifetimes shorter than the age of the solar system, even if all secondaries would survive shattering disruption over that time span. 2001 QW<sub>322</sub> cannot survive in its current state for more than 1 to 2 Gyr. 2000 CF<sub>105</sub> would most certainly have been



destroyed if it was primordial. The case of 1998 WW<sub>31</sub> is not completely settled yet. Depending on the exact parameters for its components and the relative orbit, it may or may not survive for 4 Gyr.

Up to now, we have solved the disruption equation for a single encounter. Since the number of small impactors is larger than the number of large impactors, we must also consider the effect of multiple collisions by small impactors on the secondary. In this case, the secondary will experience a random walk. The total change in velocity will grow like

$$\Delta V = \sqrt{\sum (\delta V)^2}, \quad (9)$$

where  $\delta V$  is the change of velocity due to each collision from a small impactor of mass  $m_i$ . As before,  $\delta V \propto m_i$ , and the number of collisions, in a fix timespan, is proportional to the number of impactors of mass  $m_i$ ,  $n(m_i)$ . In the following, we only consider a single power law size distribution, meaning that we will only be able to compare lifetimes or efficiency for masses on the same side of  $r_0$ . From the differential size distribution of eq. (1), the differential mass distribution is:

$$n(m_i) \propto m_i^{\frac{b-2}{3}} dm_i. \quad (10)$$

So the effect of collisions from impactors of mass  $m_i$  varies like

$$\Delta V \propto m_i^{\frac{b+4}{6}}. \quad (11)$$

Hence for  $b > -4$ , the largest impactors have the dominant effect, while for  $b < -4$ , the cumulative effect of small impactors overcomes the effect of a single collision by a big impactor. It is important to note that the effect on the velocity of the secondary is a continuous function of the impactor's mass, while the collisional erosion rate exhibits a large discontinuity for masses smaller than the critical mass for shattering and dispersing the secondary. The size distribution we have used so-far has  $b = -4.5$  in the range of sizes of the disruptive impactors (Tables 2 and 3). Hence impactors of size  $r_0$  would be collectively more efficient at disrupting the binaries. Since for  $r_i < r_0$ ,  $b = -3$ , smaller projectiles would be less efficient at disrupting the binaries. Egalizing eq. (6) and (11), and noting that the change in velocity is proportional to the square root of the timespan, we relate the disruption lifetime  $T_s$  due to multiple collisions from bodies of size  $r_0$  to the one ( $T_l$ ) computed earlier for a single collision:

$$T_s = T_l \left( \frac{m_l}{m_s} \right)^{\frac{b+4}{3}} \quad (12)$$

where  $m_l$  is the mass of the large impactor, and  $m_s$  the mass of the small impactors. Here, we have used the fact that the impactors are always small compared to the secondary, and then only the mass of the secondary governs the gravitational focusing. This reduces

the lifetimes given in Tables 2 and 3, although not in a way that changes our previous conclusions. The same 3 binaries are disrupted, maybe a little faster, and the other one can still survive for the age of the Solar System.

A word of caution is in order here. Dynamical friction from a swarm of small bodies has been said to cause a hardening of the binaries. It is not clear that bodies of radius  $r_0 = 5$  km actually participate in the dynamical friction, hence hardening the binaries instead of disrupting them. But the single disruptive collisions still occur on the time scales given in Tables 2 and 3, which then set an upper limit for the lifetimes.

In the previous calculations, we have considered a population of projectiles corresponding to today's Edgeworth-Kuiper belt. However, it seems most likely that the primordial belt had to be much more massive, as much as 100 times more massive, in order to grow bodies as large as those observed today (Stern, 1996). The increase in mass can be achieved by simply multiplying the number of objects of each size by a constant factor of order 100, retaining the same size distribution, or by keeping the same number of large bodies, and increasing the mass in small bodies. Some authors (Stern and Colwell, 1997; Davis and Farinella, 1997) have argued that the mass loss of the Kuiper belt is due to collisional erosion. From our previous estimates, we can see that a long lasting intense collisional activity can have profound effects on the KBO binaries. We now investigate these effects on the direct collision ejection mechanism.

We now suppose that the mass loss of the belt is actually due to collisional grinding. In this case, both Davis and Farinella (1997) and Stern and Colwell (1997) concluded that all primordial bodies of radius 50 km or less would have been destroyed, the ones we see now being fragments due to the shattering of bigger parent bodies. For each density and impact velocity assumed so far, we can estimate the minimum size of an impactor capable of shattering and dispersing a 50 km radius body from eq. (3). We compare this size and the corresponding collisional cross-section of a body of 50 km radius to the size and collisional cross-section of an impactor large enough to push the secondary out of its orbit, as in our second disruption mechanism. The occurrence frequency of these two types of events is the product of the collisional cross-section time the number of impactors time the intrinsic collision probability. The intrinsic collision probability has changed over the age of the solar system, and cannot be given by eq. (2) at all times, but it is the same for both types of events at any times. So we do not need to know its value to compare the frequencies. We just need to compare the cross-sections and numbers of impactors. Assuming a power-law size distribution like in eq. (1), we can derive a condition on the slope  $b$  so that a KBO binary would be disrupted by a direct impact more often than a 50 km radius body would be shattered and dispersed. This corresponds to the open region in Fig. 3, while the hashed regions correspond to slopes for which a KBO binary would be disrupted by direct impact less frequently. The current slope for large bodies,  $-4.4 \pm 0.3$  (Gladman *et al.*, 2001), is a relic of the accretion phase. Later collisional evolution

tend to push the slope toward -3.5 or even -3, starting with the small bodies. So clearly KBO binaries like 1998 WW<sub>31</sub>, 2000 CF<sub>105</sub> and 2001 QW<sub>322</sub> (large orbital separation) cannot survive an intense initial collisional activity. Even a large fraction of objects like 1998 SM<sub>165</sub> would be disrupted.

The four remaining binaries could, in some cases, resist disruption even with a size distribution shallower than  $b = -4$ . This would happen only if all collisions occur at high speed (1500 m/s). Large speeds favor shattering and dispersing over ejection since the former depends on the square of the velocity, while the latter depends on the velocity. 1997 CQ<sub>29</sub>, 1999 TC<sub>36</sub> and 2001 QC<sub>298</sub> are all very close binaries, with a large secondary, increasing their stability. 2001 QT<sub>297</sub> is a rather well separated binary (20,000 km), but has the largest of all secondaries.

## V Discussion

The existence of an object like 2001 QW<sub>322</sub>, with a lifetime of 1 to 2 Gy in the current rarefied environment means that there were, at least, between 7 and 50 similar KBO binaries 4 Gyr ago.

As expected, the most largely separated are the easiest to disrupt. In other words, the KBO binaries easiest to disrupt are also the ones that are the most difficult to create in Goldreich *et al.* (2002; L<sup>2</sup>s for two large bodies and a sea of small bodies) and Stern (2002; lcL<sup>2</sup> for late collision of two large bodies) scenarios. Weidenschilling (2002; cL<sup>2</sup>L for collision of two large bodies in the vicinity of a third large body) scenario, on the other hand, tends to create more large separation binaries. Since large separation binaries are more prone to disruption, this could reconcile cL<sup>2</sup>L with the observations, showing more binaries with small separations (4 with a distance 5000-8000 km, 3 with a distance 20,000-23,000 km and only 1 with a distance > 100,000 km) than with large separations.

L<sup>2</sup>s tend to form enough large separation binaries, if considering only their current number. However, since one must assume that there were at least an order of magnitude more large separation binaries 4 Gyr ago, this implies that at least the same increase in formation frequencies occurred for small separation binaries. This means that binaries like 1998 SM<sub>165</sub> or 1999 TC<sub>36</sub> should be at least 10 times more numerous. One possible explanation as to why this is not reflected in the current sample is that such binaries already suffer from a strong observational bias. The HST survey for KBO binaries will bring important information to try and answer this question.

An other possibility is that both L<sup>2</sup>s and cL<sup>2</sup>L have been active to form KBO binaries, L<sup>2</sup>s forming all the small separation ones, while cL<sup>2</sup>L produced a large number of large separation binaries. Finally, the short lifetime of the latter would explain the current distribution of KBO binaries.

The Stern (2002) scenario is more difficult to evaluate, partly because the main formula

(left column of p. 2301 in that paper) is obviously dimensionally wrong. Hence it is difficult to weigh the importance of each assumption. However, Stern favors a recent formation of the KBO binaries, arguing that the binary albedo could be as much as 4 times larger than usually assumed. In this case the size of the binary components would be divided by 2, and therefore the required impactor mass would decrease by almost an order of magnitude. This in turn would increase drastically their number. This last part of reasoning is true only if the albedo of all KBOs is kept at the usual value of 0.04, except for the binaries. This is quite difficult to justify. If, as seems more reasonable, all albedos have to be increased by a factor of 4, then the size distribution of KBOs would keep its shape, but shifted to sizes half the usual ones. Finally, the number of potential impactors with the required mass would be essentially the same as with the classical computation. In such a scenario, we only gain because the critical specific energy  $Q_D^*$  is an increasing function of mass.

We have seen that if the much denser initial environment lasts long enough to allow the elimination of most of the mass of the Kuiper belt through collisional grinding (Davis and Farinella, 1997; Stern and Colwell, 1997), then all the large separation KBO binaries would be disrupted. Simultaneously, many of the small separation binaries would also be disrupted. Since it seems impossible to create the large separation binaries in the current environment, this implies that the dense initial environment did not last long enough to allow for collisional grinding. Furthermore, collisional grinding can be effective at removing mass only for very steep slopes ( $b \lesssim -4.5$ ) down to very small sizes, which is steeper than that predicted by accretion models (Davis *et al.*, 1999; Kenyon and Luu, 1999), at least in the 1–10 km range. Hence, the mass reduction of the Kuiper belt by a factor of 100 must result from a dynamical mechanism, as proposed by Gomes (2003) and Levison and Morbidelli (2003). This explanation is actually supported by the current inclination of the KBOs which is much larger than their eccentricity on average (Gladman *et al.*, 2001).

This also allows to address the main criticism of the Weidenschilling scenario by Golreich *et al.* that Weidenschilling did not propose a mechanism for disposing of the surplus of large bodies needed at the beginning. If it is the case that dynamics rather than collision erosion is responsible for eliminating most the Kuiper belt mass, then the belt erosion is independent of the size of the objects. In such a case, one can easily dispose of 99% of the belt mass, and in particular of numerous large bodies.

## VI Summary

In this paper, we have shown that the stability of the KBO binaries with respect to perturbations other than the usual shattering and dispersing of fragments had to be investigated. Ejection of the secondary from its orbit around the primary by a direct collision of a rather small impactor turns out to be an efficient way to eliminate KBO

binaries.

The lifetime of 2001 QW<sub>322</sub> is 1 to 2 Gy, and hence there must have been at least 10 times more similarly widely separated binaries formed at the beginning. Therefore, both Goldreich *et al.* (2002) and Weidenschilling (2002) scenarios of primordial formation must have been acting, Goldreich *et al.* mechanism forming most of the close binaries, Weidenschilling's forming most of the large separation binaries.

Unless one can find a viable mechanism for forming numerous KBO binaries in the current dynamical and collisional environment, we also showed that the erosion of the Kuiper Belt cannot be due to collisional grinding. It has to be the result of some dynamical effect that occurred on a time scale shorter than that necessary to collisionally erode most of the belt.

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Object name	Merline <i>et al.</i> (2003)			Stern (2002)			$\Delta$ (AU)
	$R_P$ (km)	$R_S$ (km)	Separ. (km)	$R_P$ (km)	$R_S$ (km)	Separ. (km)	
1998 WW <sub>31</sub>	75	60	22,300	169	141	22,000	44.95
2001 QT <sub>297</sub>	290	207	20,000	223	173	20,000	44.80
2001 QW <sub>322</sub>	100	100	130,000	78	65	130,000	44.22
1999 TC <sub>36</sub>	370	132	8,000	293	107	11,000	39.53
1998 SM <sub>165</sub>	225	94	6,000	194	81	8,000	47.82
1997 CQ <sub>29</sub>	150	150	5,200	177	177	5,600	45.34
2000 CF <sub>105</sub>	85	53	23,000	117	79	23,000	44.20
	$\Delta M = 0$			$\Delta M = 2.2$			
2001 QC <sub>298</sub>	150	150	5,000	199	72	5,000	41.04

Table 1: Characteristics of the binaries, according to Merline *et al.* (2003) (columns 2 to 4), and Stern (2002) (columns 5 to 7).  $R_P$  is the radius of the primary,  $R_S$  the radius of the secondary,  $\Delta$  the heliocentric distance, and columns 4 and 7 give the distance between the 2 components of the binary. Values for 2001 QC<sub>298</sub> are given assuming equal size of both components (columns 2 to 4) or a difference in magnitude of 2.2 (columns 5 to 7). The assumed albedo is 0.04 in all cases, except for 1998 WW<sub>31</sub>, for which Merline *et al.* assumed an albedo of 0.054. Stern used a density of 2 g/cm<sup>3</sup>, while Merline *et al.* assumed a more conventional density of 1 g/cm<sup>3</sup>.



Object name	Shattering		Collisional unbinding		Gravity		Shattering		Collisional unbinding		Gravity	
	$R_{shat}$ (km)	$T_{shat}$ Gyr	$R_h$ (km)	$T_h$ Gyr	$R_g$ (km)	$T_g$ Gyr	$R_{shat}$ (km)	$T_{shat}$ Gyr	$R_h$ (km)	$T_h$ Gyr	$R_g$ (km)	$T_g$ Gyr
WW <sub>31</sub>	18.5	38	6.3	1.3	288	20	80.5	830	25	25	492	59
QT <sub>297</sub>	108.5	1200	43	72	620	250	109.5	1500	35.5	54	492	100
QW <sub>322</sub>	38	150	9.5	1.9	620	3.4	26	96	6	0.85	492	1.3
TC <sub>36</sub>	56.5	330	34.5	75	620	1200	54	380	26.5	46	492	320
SM <sub>165</sub>	34.5	130	20	24	288	850	36	180	17	19	492	270
CQ <sub>29</sub>	68	470	30	39	288	630	113.5	1600	42.5	89	492	570
CF <sub>105</sub>	15.5	27	5.7	1.1	288	21	34.5	160	11.5	5.2	492	29

Table 2: Minimum size of impactor (even columns) and corresponding lifetime (odd columns) for the KBO binaries, for each of the three disruption mechanisms: shattering, hitting, gravity perturbation. Binary parameters correspond to Merline *et al.* (2003) for columns 2 to 7, and to Stern (2002) for columns 8 to 13.

Disruption mechanism	$\rho = 1 \text{ g cm}^{-3}$				$\rho = 2 \text{ g cm}^{-3}$			
	$\Delta M = 0$		$\Delta M = 2.2$		$\Delta M = 0$		$\Delta M = 2.2$	
	$R_{shat}$ (km)	$T_{shat}$ Gyr	$R_h$ (km)	$T_h$ Gyr	$R_g$ (km)	$T_g$ Gyr	$R_g$ (km)	$T_g$ Gyr
Shattering	68	470	24	63	88.5	990	30.5	130
Hitting	30	40	15	15	33.5	57	17	21
Gravity	288	650	288	790	492	520	492	580

Table 3: Same as Table 2, but for the various parameters for 2001 QC<sub>298</sub>.

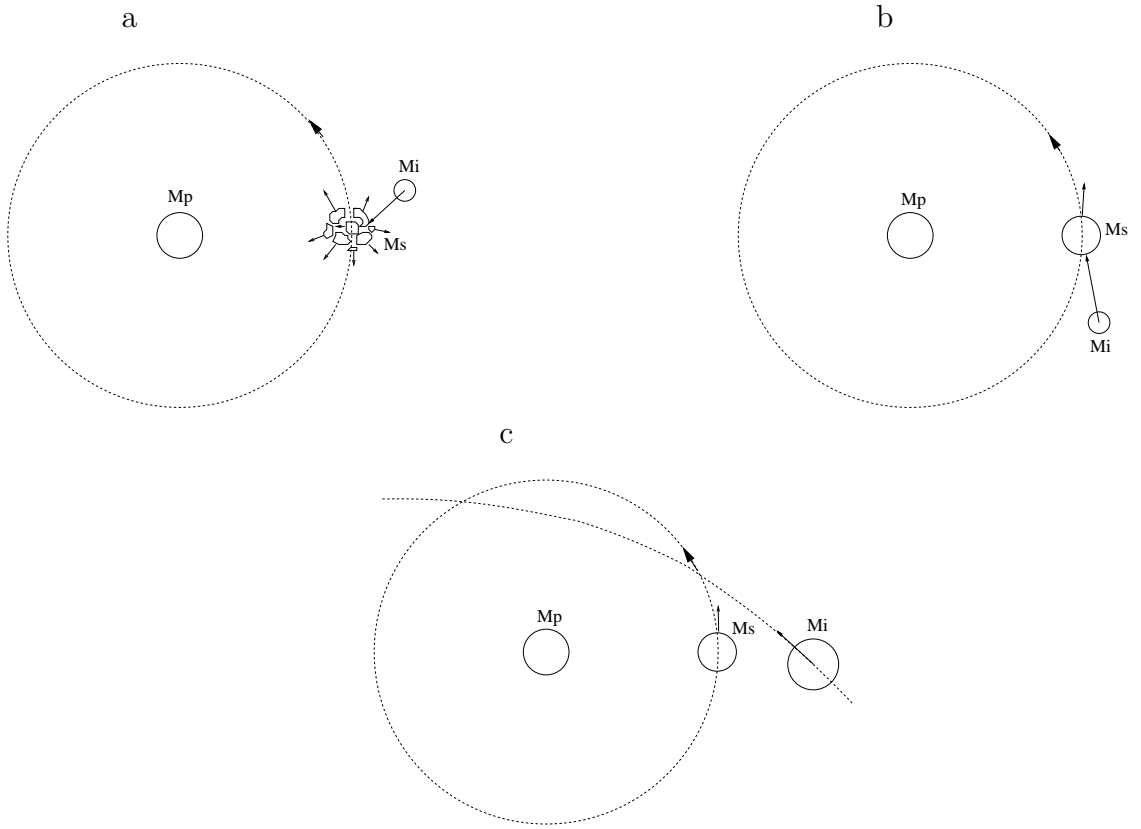


Figure 1: (a): The secondary is shattered and its fragments are dispersed due to a high-velocity impact. (b): The secondary is kicked off its orbit around the primary due to a direct collision by another TNO. (c): The secondary is dislodged from its orbit around the primary due to the gravitational perturbation from a passing TNO.

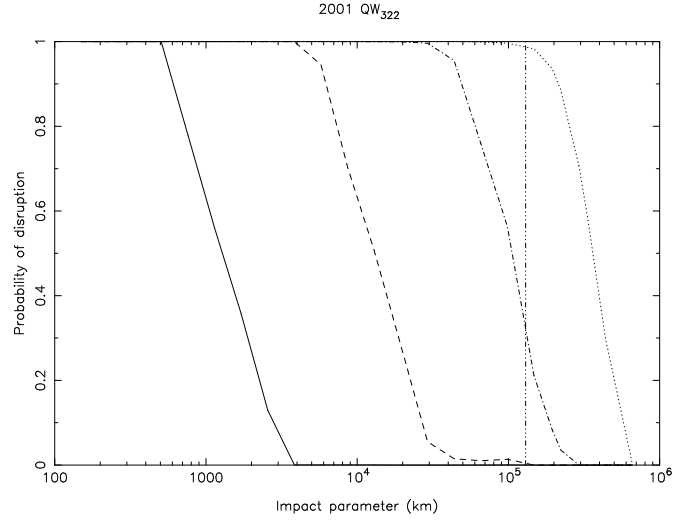


Figure 2: Probability of disruption of 2001 QW<sub>322</sub> due to a projectile arriving at 500 m/s with mass of  $10^{19}$  (solid line),  $10^{20}$  (dashed line),  $10^{21}$  (dash-dotted line) and  $10^{22}$  kg (dotted line). The dash-triple dot line indicates the orbital separation of 2001 QW<sub>322</sub>.

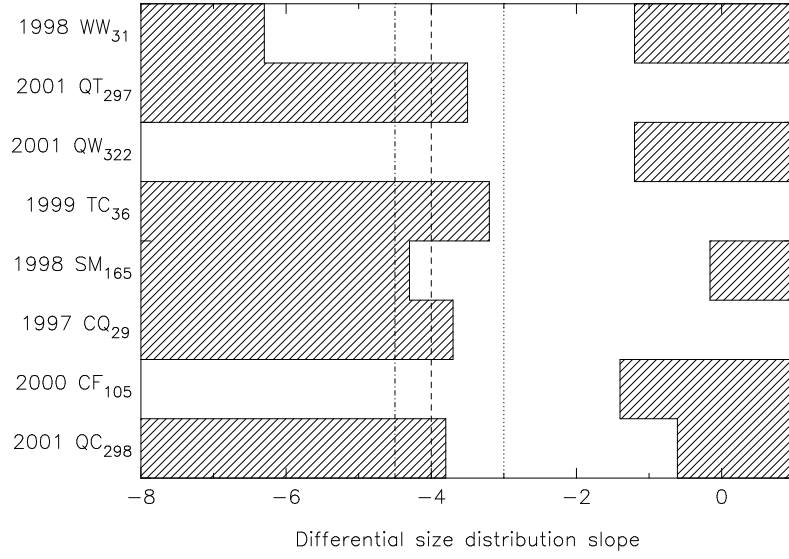


Figure 3: The hashed regions correspond to slopes of the differential size distribution for which collisional disruption of a binary occurs less frequently than shattering and dispersing of a 50 km body in the massive primordial environment. The -4 slope (dashed line) is the limit below which multiple collisions of small impactors are more efficient than single collisions of larger impactors. The dash-dotted line corresponds to the large-end size distribution exponent in eq.(1), the dotted line corresponding to the small-end.